Simple pressure switches comprise transducers, comparators, and op amps

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With a few added components, circuits that condition pressure-transducer signals can provide a logic-level output that changes state when a pressure crosses a threshold.

In concept, a pressure switch is simple. Its major subsystems are the pressure sensor, the signal conditioning (gain) stage, and output stages that employ comparator ICs and op amps. Just a few added components are necessary to let circuits that condition pressure-transducer signals deliver a logic-level output that changes state when a pressure crosses a threshold or thresholds. Such an output can drive an LED, a microcontroller input, or an electronic switch. The user-programmed threshold, or reference voltage, determines the pressure at which the output state switches. In addition, an optional user-defined hysteresis setting eliminates multiple output transitions when the pressure-sensor voltage is near the threshold.

Motorola's MPX2000 Series sensors are temperature-compensated pressure transducers whose offset and full-scale span are precisely trimmed. These sensors are available in full-scale pressure ranges from 10 to 700 kPa (kiloPascals), or 1.5 to 100 psi. Although the specifications in the data sheets apply only with a 10V supply (see **Table 1**), the output of these devices is ratiometric with the supply voltage. For example, at a supply voltage of 16V—the absolute maximum rating—these sensors produce a differential output voltage of 64 mV when subjected to the rated full-scale pressure. One exception is the 10-kPa MPX2010, which because of its slightly lower sensitivity, has a full-scale span of only 40 mV. Because the output is small even at the maximum supply voltage, some signal conditioning is usually required. For this design, an MPX2100 with a 5V supply provides a maximum sensor output of 20 mV. Signal conditioning boosts the sensor output to a 4V swing (span).

The amplifier circuitry (see **Fig 1**), consists of two op amps. This interface circuit has a much lower component count than conventional quad op-amp instrumentation amplifiers. The double-op-amp design offers the high input impedance, low output impedance, and high gain desired for a transducer interface and performs a differential to single-ended conversion. Set the gain by the following equation:

$$\text{GAIN}=1+(R_6/R_5),\text{ where } R_6=R_3 \text{ and } R_4=R_5.$$

For this specific design, the gain is set to 201 by establishing R_6=20 kΩ and R_5=100Ω. Using these values and setting $R_6=R_3$ and $R_4=R_5$ gives the desired gain without loading the reference voltage divider formed by R_1 and R_{OFF}. Choosing R_{OFF} sets the offset voltage via this voltage divider, allowing adjustment of the offset according to the needs of each application.

The comparison stage is the heart of the pressure-switch design. This stage converts the analog voltage output to a digital output, as dictated by the comparator's threshold. The comparison stage has a few design issues that must be addressed:

The first is the threshold for which the output switches

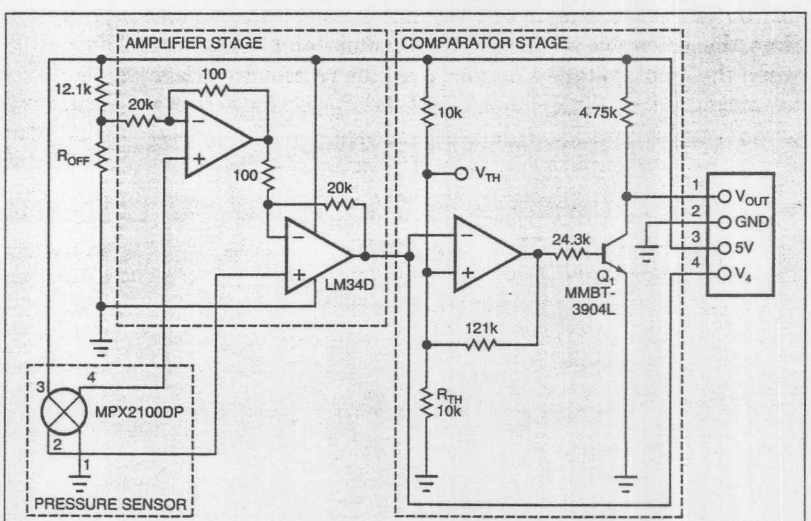

Fig 1—The pressure switch consists of the sensor, an instrumentation amplifier, and a comparator.

must be programmable. You set the threshold by dividing the supply voltage with resistors R_7 and R_{TH}. In **Fig 1**, the threshold is set at 2.5V because $R_7=R_{TH}=10\ k\Omega$.

The circuit should include a means of introducing an appropriate amount of hysteresis. Hysteresis prevents multiple transitions from occurring when a slowly changing signal varies around the threshold. Positive feedback produces the hysteresis. The value of the feedback resistor, R_H, determines the amount of hysteresis in accordance with equations in the following section.

Ideally, the comparator's logic-level output should swing from one supply rail to the other. In practice, this is not possible. Thus, the goal is to swing as high and low as possible for a given set of supplies. With the greatest possible difference between logic states, you avoid having a microcontroller read the switch level as being in an indeterminate state. For compatibility with CMOS circuitry and to avoid microcontroller timing-delay errors, the comparator must also switch sufficiently fast.

By using two comparators, you can implement a window comparator. You can use the window comparator to monitor whether the applied pressure is within a set range. By adjusting the input thresholds, you can customize the window width for a given application. As with the single-threshold design, positive feedback can provide hysteresis for both switching points.

Sample comparator circuits

We built and evaluated several comparator circuits, including ones that used the LM311 comparator, the LM358 op-amp (with and without an output transistor stage), and the LM339. We evaluated each comparator for output voltage levels (dynamic range), transition speed, and the relative component count required for the complete pressure-switch design. This comparison appears in **Table 2**.

The LM311 chip is designed specifically for use as a comparator and thus has short delay times, a high slew rate, and an open-collector output. A pullup resistor at the output is all you need to obtain a rail-to-rail output. Additionally, the LM311 is a reverse-logic circuit; that is, for an input lower than the reference voltage, the output is high. Likewise, when the input voltage is higher than the reference voltage, the output is low. **Fig 2** shows the LM311 stage with a threshold-setting resistor divider, a hysteresis resistor, and the open-collector pullup resistor. Based on its performance, this circuit suits many types of applications, including interfacing to microprocessors.

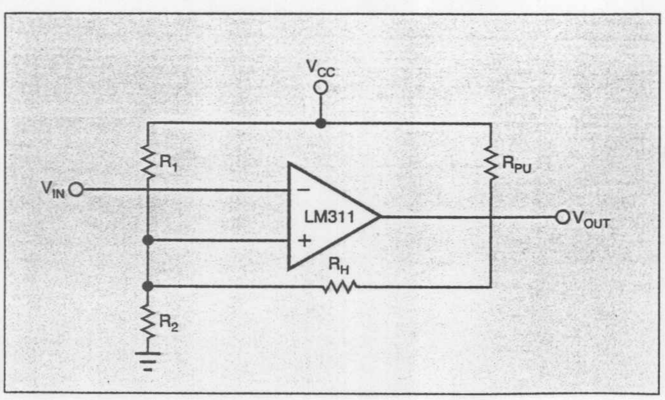

Fig 2—A simple comparator consists of an LM311, a pair of resistors that establish the hysteresis, a resistor that, in conjunction with the feedback network, establishes the offset, and a pullup resistor.

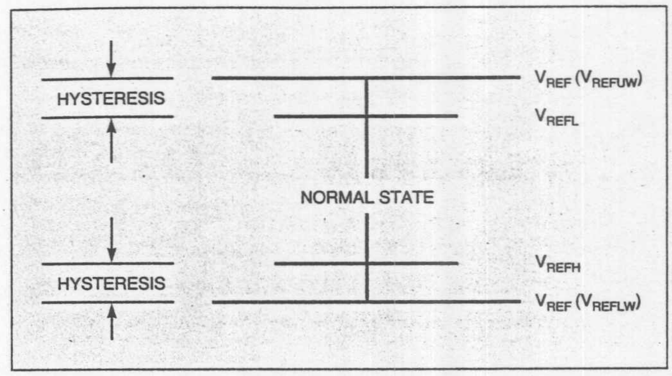

Fig 3—If the normal state is below the reference voltage, V_{REFL} is below V_{REF} by the desired amount of hysteresis, and you use V_{REFH} only to calculate a more precise value for V_{REF}. (Use V_{REFL} to calculate R_H.) If the normal state is above the reference voltage, V_{REFH} is above V_{REF} by the desired amount of hysteresis, and you use V_{REFL} only to calculate a more precise value for V_{REF}. (Use V_{REFH} to calculate R_H).

You can calculate the amount of hysteresis from the following equations:

$V_{REF}=(R_2/(R_1+R_2))\cdot V_{CC}$, neglecting the effect of R_H;
$V_{REFH}=((R_1R_2+R_2R_H)/(R_1R_2+R_1R_H+R_2R_H))\cdot V_{CC}$;
$V_{REFL}=(R_2R_H/(R_1R_2+R_1R_H+R_2R_H))\cdot V_{CC}$;
$HYSTERESIS=V_{REF}-V_{REFL}$, when the normal state is below V_{REF};
or $HYSTERESIS=V_{REFH}-V_{REF}$, when the normal state is above V_{REF}.

See **Fig 3** for an illustration of hysteresis and the relationship between these voltages.

The initial calculation for V_{REF} is slightly in error because it neglects the effect of R_H. To establish a precise value for V_{REF} (including R_H in the circuit), recompute R_1 taking into account that V_{REF} depends on R_1, R_2, and R_H. It turns out that when the normal state is below V_{REF}, R_H is in parallel with R_1:

$$V_{REF}=(R_2/(R_1||R_H)+R_2)\cdot V_{CC},$$

which is identical to the equation for V_{REFH}.

Alternately, when the normal state is above V_{REF}, R_H is in parallel with R_2:

$$V_{REF}=((R_2||R_H)/(R_1+(R_2||R_H))\cdot V_{CC},$$

which is identical to the equation for V_{REFL}. You can use these two additional equations for V_{REF} to calculate a more precise value for V_{REF}.

Note that we chose V_{REF}, V_{REFH}, and V_{REFL} for each application, depending on the desired switching point and hysteresis values. Also, you must specify which range—either above or below the reference voltage—is the desired normal state (see **Fig 3**). Referring to **Fig 3**, if the normal state is below the reference voltage, V_{REFL} is below V_{REF} by the desired amount of hysteresis and V_{REFH} is used only to calculate a more precise value for V_{REF}, as explained above. (Use V_{REFL} to calculate R_H.) Alternately, if the normal state is above the reference voltage, V_{REFH} is above V_{REF} by the desired amount of hysteresis, and

Table 1—MPX2100 electrical characteristics at V_S=10V, T_A=25°C

Characteristic	Symbol	Min	Typical	Max	Unit
Pressure range	P_{OP}	0		100	kPa
Supply voltage	V_S		10	16	V dc
Full-scale span	V_{FSS}	38.5	40	41.5	mV
Zero-pressure offset	V_{OFF}		0.05	0.1	mV
Sensitivity	S		0.4		mV/kPa
Linearity			0.05		%FSS
Temperature effect on span			0.5		%FSS
Temperature effect on offset			0.2		%FSS

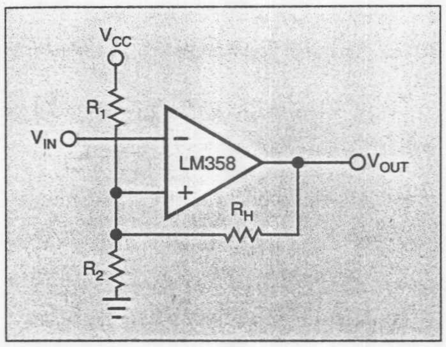

Fig 4—Besides the LM358, you need only three components—resistors—to build this comparator circuit.

you need only use V_{REFL} to calculate a more precise value for V_{REF}. (Use V_{REFH} to calculate R_H.)

LM358 in a comparator circuit

Fig 4 details the LM358 op-amp comparator stage, and **Table 2** shows its performance. Because the LM358 is an operational amplifier, it has neither the fast slew rate nor the open-collector output of a comparator IC. Comparing the LM358 and the LM311 (**Table 2**), the LM311 is better for logic and switching applications because its output extends nearly from rail to rail and has a sufficiently high switching speed. The LM358 performs well in applications where the switching speed and logic-state levels are not critical (for example, driving an LED). Use the same equations and procedure presented for the LM311 to accomplish the design of the LM358 comparator. This circuit is also reverse logic.

Fig 5 shows the LM358 with a transistor output stage. This circuit has performance similar to that of the LM311 comparator: Its output reaches the upper rail, and its switching speed is comparable to the LM311's. This enhanced performance does, however, require an additional transistor and base resistor. Referring to **Fig 1**, note that we chose this comparator topology for the pressure-switch design. The LM324 is a quad op-amp whose amplifier characteristics are equivalent to those of the LM358.

You can design this comparator circuit with the same equations and procedure as those for the other two circuits. The values chosen for R_B and R_{PU} give a 5:1 ratio of Q_1's collector current to its base current to ensure that Q_1 is well-saturated. V_{OUT} can pull down very close to ground when Q_1 is on. Once you choose the 5:1 ratio, the actual resistance values determine the desired switching speed for turning Q_1 on and off. Also, R_{PU} limits the collector current to less than the maximum specified for the output transistor (See **Fig 1**). Unlike the other two circuits, this circuit is positive logic due to the additional inversion created at the output- transistor stage.

Using two voltage references to detect when the input is within a certain range is another possibility for the pressure-switch design. **Fig 6** shows the window-comparator. The LM339 is a quad-comparator IC with open-collector outputs, and its performance is similar to that of the LM311.

You use a slightly different procedure to obtain the correct amount of hysteresis and to determine the input reference voltages than you do with other circuits. You can use the following equations to calculate the hysteresis and reference voltages. Referring to **Fig 3**, V_{REFUW} is the upper-window reference voltage and V_{REFLW}, the lower. Remember that "reference voltage" and "threshold voltage" are interchangeable terms.

For the upper-window threshold, choose the value for V_{REFUW} and R_1 (for example, 10 kΩ). Then, by voltage division, calculate the total resistance of the combination of R_2 and R_3, identified as R_{23}, to obtain the desired value for V_{REFUW}, neglecting the effect of R_{HU}:

$$V_{REFUW}=(R_{23}/(R_1+R_{23}))\cdot V_{CC}.$$

You can use the following equation to calculate the amount of hysteresis:

$$V_{REFL}=(R_{23}R_{HU}/(R_1R_{23}+R_1R_{HU}+R_{23}R_{HU}))\cdot V_{CC}.$$

Notice that the upper-window reference voltage, V_{REFUW}, is now equal to its V_{REFL} value, because at this moment, the input voltage is above the normal state.

$$\text{HYSTERESIS}=V_{REFUW}-V_{REFL},$$

where V_{REFL} gives the desired amount of hysteresis for the application.

The initial calculation for V_{REFUW} is slightly in error because it neglects the effect of R_{HU}. To establish a precise value for V_{REFUW} (including R_{HU} in the circuit), recompute R_1,

Table 2—Comparator circuits' performance characteristics

Characteristic	LM311	LM358	LM358+ Transistors	Unit
Switching speeds:				
Rise time	1.4	5.58	2.2	μsec
Fall time	0.04	6.28	1.3	μsec
Output levels				
V_{OH}	4.91	3.64	5	V
V_{OL}	61.1	38	66	mV
Circuit logic type	Negative	Negative	Positive	

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taking into account that V_{REFUW} depends on R_2 and R_3 and the parallel combination of R_1 and R_{HU}. You can calculate this more precise value with the following equation:

$$V_{REFUW}=(R_{23}/(R_1||R_{HU})+R_{23})\cdot V_{CC}.$$

For the lower-window threshold, choose the value for V_{REFLW}.

$$V_{REFLW}=(R_3/((R_1||R_{HU})+R_2+R_3))\cdot V_{CC},$$

where $R_2+R_3=R_{23}$ from the above calculation.

To calculate the hysteresis resistor, remember that in the normal state, the input to the lower comparator is one-half V_{IN}, because $R_4=R_5$. When V_{REFLW} is above one-half of V_{IN}—that is, when the input voltage has fallen below the window—R_{HL} parallels R_4, thus loading down V_{IN}. The resulting input to the comparator can be referred to as V_{INL} (a lower input voltage). To summarize, when the input is within the window, the output is high and only R_4 connects to ground from the comparator's positive terminal. This establishes half of V_{IN} to be compared with V_{REFLW}. When the input voltage is below V_{REFLW}, the output is low and R_{HL} is effectively in parallel with R_4. By voltage division, less of the input voltage falls across the parallel combination of R_4 and R_{HL}, demanding a higher input voltage at V_{IN} to make the noninverting input exceed V_{REFLW}. Therefore, the following equations result:

$$\text{HYSTERESIS}=V_{REFLW}-V_{INL}.$$

Choose $R_4=R_5$ to simplify the design.

$$R_{HL}=(R_4R_5)(V_{REFLW}-V_{INL}-V_{CC})/(R_4+R_5)(V_{INL}-V_{REFLW}).$$

As explained above, because R_4 and R_5 divide the input voltage by two, you must make all calculations relative to half the value of V_{IN}. Therefore, for a hysteresis of 200 mV (relative to V_{IN}), the above equations must use half this value, or 100 mV. Also, if you want a V_{REFLW} value of 2V (relative to V_{IN}), use 1V in the above equations; also, divide the value of V_{INL} by two.

You can also design the window comparator using operational amplifiers and the same equations used for the LM339 comparator circuit. For the best performance, however, include a transistor-output stage in the design.

The pressure-switch design uses a comparator to create a logic-level output by comparing the pressure-sensor output voltage and a user-defined reference voltage. The flexibility of this low-component-count, high-performance design makes it compatible with many applications. The design presented here uses an op-amp with a transistor output stage, yielding excellent logic-level outputs and output-transition speeds for many applications. Finally, we evaluate several other comparison-stage designs, including a window comparator, and compare them for overall performance. EDN

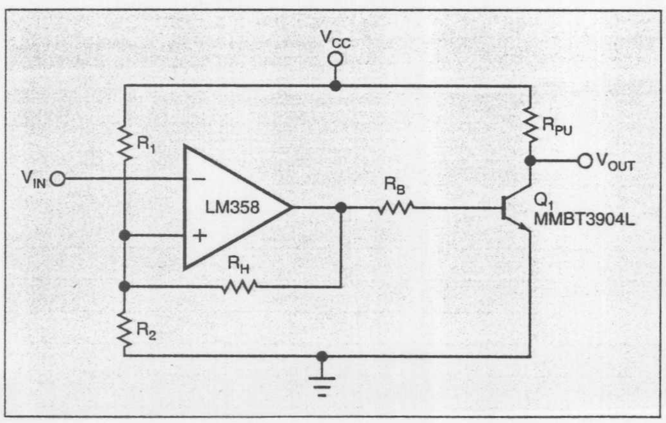

Fig 5—You can improve the performance of the LM358 comparator by adding a transistor and two resistors.

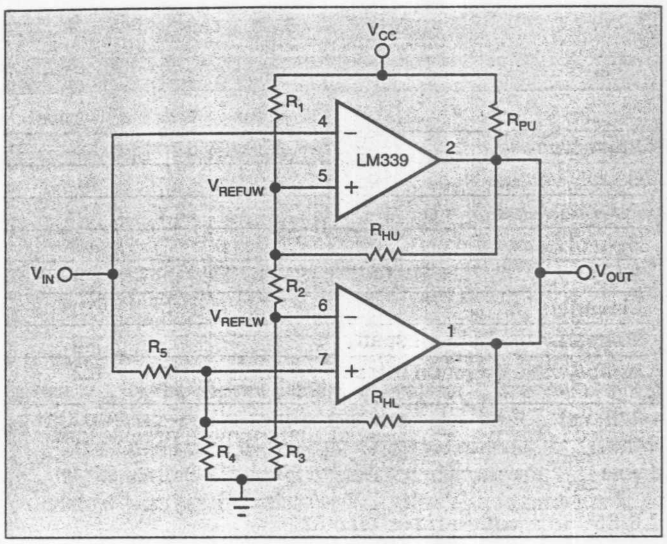

Fig 6—Two of the four comparator stages in an LM339 plus a handful of resistors comprise a window comparator whose logic-level output indicates whether a pressure lies within or outside of a pair of thresholds.

Authors' biographies

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